A Four-Year Survey of Terrestrial Gamma-ray Flashes (TGFs) with Fermi LAT

J. Eric Grove
Naval Research Laboratory

A. Chekhtman (GMU-NRL), M.S. Briggs (UAH), V. Connaughton (UAH), G.J. Fishman (MSFC)
on behalf of the LAT Collaboration
Introduction

• What is a TGF and why should you care?
  – Intense (sub-)millisecond flash of MeV gamma rays from thunderstorms
  – Power in MeV flash comparable to power in lightning bolt
    • Few x 10^{17} MeV gammas in few hundred microsec
  – Thunderstorms are most powerful natural terrestrial particle accelerator
    • Accelerator at ~10-15 km altitude, accessible by aircraft

Recent review: Dwyer, Smith, & Cummer, Space Sci Rev 2012

• Present model, inside thundercloud
  – Relativistic Runaway Electron Avalanche (RREA) with feedback
    • Strong E field accelerates electrons to relativistic energies before they range out
    • γ-rays from electron bremsstrahlung
    • Predict ~7 MeV exponential γ-ray cutoff

Gurevich et al. 1992; Babich et al. 1998; Dwyer 2003; ...; Dwyer 2011
Introduction – Above 10 MeV

• Why is LAT useful?
  – AGILE spectral result inconsistent with RREA theory
    • Power law tail to ~100 MeV
    • Avalanche electron $<E> \sim 7$ MeV
  – More recently, two populations in AGILE
    • (Marisaldi, Frascati 2012)
    • Soft spectral class: ~90%
      – RREA spectrum
      – Typical TGF properties
    • Hard spectral class: ~10-15%
      – Hard power law spectrum
      – Relationship to lightning?

– Fermi LAT
  • Large area, high segmentation -> high sensitivity with minimal pile-up
  • Low deadtime: 26.5 µs per event
  • Imaging and spectroscopy
Detecting TGFs in LAT

• Two observation types with Fermi LAT
  – Sky survey
    • Advantages
      – High duty cycle (>95%)
      – Good effective area
      – Many TGFs, large sample
    • Disadvantages
      – Trigger and on-board filter reject many LAT events within TGFs
  – Nadir oriented
    • Approved Cycle 4 and 5 GI programs, 25 observations each
    • Advantages
      – Best effective area
      – Trigger config optimized
      – On-board filter disengaged
    • Disadvantages
      – Very low duty cycle (~1%)
      – LAT not in sky survey
      – Small TGF sample
Summary of nadir observations

- Special nadir-observing program in progress
  - 27 three-orbit nadir pointings from 26 July 2011 to 5 Oct 2012
  - Cycle 5 program approved; expect 22 more nadir pointings to Aug 2013
- Status to date of nadir observing
  - Twenty-two TGFs detected so far in special nadir-observing configuration
  - LAT clearly, unambiguously detects GBM TGFs
  - Primary goals
    - Measure spectral hardness and endpoint from ensemble of TGFs
    - Measure energy flux, lightcurve
    - Search for weak, hard-spectrum TGFs

---

![Graphs showing energy flux vs. time for two TGFs: Preliminary TGF111021001 and Preliminary TGF110829562. The graph on the left shows a sharp peak at time zero, labeled Preliminary, with a y-axis in logarithmic scale ranging from $10^3$ to $10^5$ energy flux above 2 MeV cm$^2$/s. The graph on the right shows an abrupt turn-off at time 0.1 ms with a y-axis in logarithmic scale ranging from $10^4$ to $10^6$ energy flux above 2 MeV cm$^2$/s.](image-url)
Detecting TGFs in LAT

- LAT trigger and filter
  - Which TGF photons cause trigger and read out?
    - Predominantly ~ 10 MeV
      - Only weakly a fcn of TGF spectral shape
    - Very large trigger effective area. Compare at 10 MeV:
      - ~2000 cm² near boresight, ~500 cm² at 130 deg
      - GBM BGO ~ 200 cm² per detector
      - AGILE MCAL ~ 500 cm²
    - Once triggered, detectors register photons of much lower energy
      - TKR above ~100 keV; CAL above 2 MeV
      - Detectors and electronics “integrate” deposited energy over ~3 to 5 µs
  - On-board filter
    - Rejects 80-90% of triggered events
      - (>60% of TGF events rejected)

- Sky survey dataset is not optimal
  - Can fail to detect TGF
  - Many LAT events within TGF are lost

References:
GM – Meegan et al. 2009
Event display

- Characteristic of TGFs in LAT
  - Trigger request rate can peak >1 MHz
    - Algorithm: search for anomalously high rate
  - Events are complex
    - High multiplicity, i.e. not single-photon events
    - Typically not one ~100 MeV photon or one ~1 GeV photon; instead ~30 or ~300 photons (respectively) from typical RREA spectrum in ~5 µs

- Brightest sky-survey TGF
  - ~500 photons in ~5 µs integration
• Three TGF event displays
  – Typical or dimmer than average
TGF search during LAT sky survey

• Search algorithm
  – Find extreme outliers in trigger rate
  – Remove coincident cosmic ray showers
  – Inspect event displays to verify

• TGFs from sky-survey dataset (Aug 2008 – Jun 2012)
  – 319 high-confidence TGFs in LAT

• Comparison with GBM
  – Consistent with GBM list?
    • ~66% of LAT-detected TGFs in sky survey are also detected by GBM
    • ~80% in nadir attitude
  – Why not in GBM list?
    • Not in TTE box
      – GBM on-board flash trigger: ~10% efficiency of ground TTE search
    • Conservative detection algorithm
      – Low false-positive rate
• Geographic distribution (location of Fermi at time of TGF)
  – Active TGF regions are active thunderstorm regions
  – Geographic correlation
    • Land masses, active thunderstorm regions. Coastal storms
    • Note: not possible to measure TGFs within SAA

  – Consistent with historical record of TGFs
Temporal distributions

• Annual variation of latitude
  – Follows distribution of thunderstorm activity
  – Active in local summer

• Consistent with known TGF behavior
  – BATSE, RHESSI, GBM
Temporal distributions

- **Diurnal variation**
  - Peak in local afternoon
  - Rare in local morning
  - High in pre-dawn hours
    - relative to thunderstorm activity

- **Consistent with known TGF behavior**
  - BATSE, RHESSI, GBM
• Duration of MeV flash
  – Typically <1 ms

• Consistent with known TGF behavior
  – RHESSI, GBM
    • (Shorter than AGILE TGFs)
  – Compare t90 from GBM sample

– Caveat
  • Durations from LAT sky survey sample are susceptible to biases
    – On-board filter
    – Max readout rate: 1 event per 26.5 µs

---

**TGF durations**
Imaging TGFs with LAT

- Standard LAT photon direction and source image reconstruction difficult for TGFs
  - Too many near-simultaneous photons; Too much Compton scattering
- Use shadow cast by CAL on TKR

XZ projection

Direction from TGF in XZ plane

YZ projection

Direction from TGF in YZ plane

XY projection

Run Id 303664775 -- Event Id 14425340

TGF100816.695
Geolocation with LAT and VLF radio

- VLF lightning location networks (WWLLN, ENTLN)
  - Typically ~20 km location uncertainty from VLF
  - Good fraction of TGFs have coincident VLF pulse (~10% to ~50%)
- Compare with LAT shadow directions
  - VLF pulse is temporally and spatially coincident with TGF

• More to come...
Conclusions

• LAT has large effective area for TGF detection at 10 MeV and above
• LAT clearly, unambiguously detects TGFs in sky survey and special nadir obs
  – LAT joins GBM, RHESSI, and AGILE
• Spectral measurements in progress
• First simultaneous geolocations in gamma rays and VLF
  – Gamma rays and VLF transient are temporally and spatially coincident
Backup slides
Acknowledgements

• We wish to thank the World Wide Lightning Location Network (http://wwlln.net), a collaboration among over 50 universities and institutions, and the Earth Networks Total Lightning Network (http://earthnetworks.com/Products/TotalLightningNetwork.aspx) for providing the lightning location data.

• The Fermi LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

• This work was performed at NRL under sponsorship by NASA DPR S-15633-Y.
Comparison with GBM list

• Why not identical?
  – TGFs in GBM missed by LAT
    • On-board filter and LAT trigger logic
      – Bright TGFs: Too many ACD hits
      – Weak TGF: Events lost to filter
    • Unfavorable geometry
      – TKR occulted by CAL for TGFs near -Z axis
  – TGFs in LAT missed by GBM
    • Not in TTE box
      – GBM on-board flash trigger: ~10% efficiency of ground TTE search
    • Conservative detection algorithm
      – Low false-positive rate
    • Unfavorable geometry
      – Occulted by CAL